Damage from the april-may 2015 gorkha earthquake sequence in the Solukhumbu district (Everest region), Nepal

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DAMAGE FROM THE APRIL-MAY 2015 GORKHA EARTHQUAKE SEQUENCE IN THE SOLUKHUMBU DISTRICT (EVEREST REGION), NEPAL

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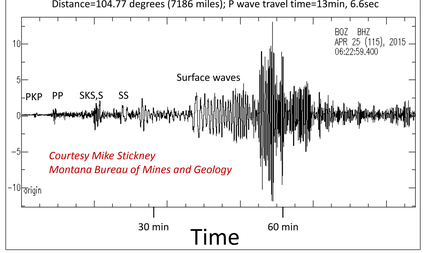
ABSTRACT: Rapid assessments of landslides (including other mass movements of rock, snow and ice) as well as human impacts were conducted by many organizations immediately following the 25 April 2015 M7.8 Gorkha earthquake and its aftershock sequence. In particular, a NASA-led satellite mapping campaign identified over 4,300 coseismic and post-seismic landslides throughout Nepal, largely concentrated in the "down-dropped northern tectonic block" well north of Kathmandu in the Greater Himalaya (Kargel et al., 2016). The **Solukhumbu District** lies at the eastern margin of this zone, near the epicenter of the 12 May 2015 M7.3 aftershock. Given the enormous cultural and economic value of the Khumbu region to Nepal, we conducted two post-monsoon ground assessments of geomorphic and structural damage in the fall of 2015, and a third ground assessment of rebuilding efforts in May, 2016. While landslides and other mass movements were not as extensive as those to the west, numerous landslides and slumps were identified, mostly on steep, convex-up, east-facing slopes where the dip of metamorphic foliation (Namche orthogneiss and related rocks) is towards the Dudh Kosi River channel. Also, building damage was more extensive where villages were located on terraces of unconsolidated sand and gravel perched above the Dudh Koshi River (Nakchun Village). The area upstream from Phakding experienced several co-seismic mass movements on steep slopes that had clearly failed before (previous temblors?), as evidenced by old vegetated slump blocks and steep, unstable hummocky terrain. Particularly hard-hit was the Sherpa village of Thame northwest of Namche Bazaar, constructed on unconsolidated, water-saturated glacial outwash between two lateral moraines at the mouth of the Thame Khola Valley. Aside from Thame, one is struck by the randomness of structural damage in many Sherpa villages, reflecting micro-ground conditions beneath buildings and the style and/or age of construction (dry-stacked fieldstone versus the use of mud or cement mortar, the presence of wire mesh or gabion bands/spacers within stone walls, etc.). Fresh valley-flank slumps and landslides were markedly less obvious further north (towards Everest) where wide glacial valleys exist, although evidence of large rock falls and other mass movements in the past is clearly present.

Vertical ground motion recorded at the BOZ seismograph station for the April 25, 2015 Nepal earthquake; magnitude 7.8

Distance=104.77 degrees (7186 miles); P wave travel time=13min, 6.6sec



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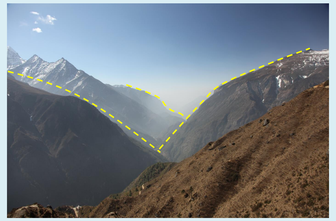
Recent Advances in Geomorphology, from the Mountains to the Coast (Posters)
Session No. 59, Paper No. 59-4, Booth# 17
Sunday, 25 September 2016: 9:00 AM-5:30 PM
Exhibit Hall E/F (Colorado Convention Center)

Valley profile convexity:

The photo above shows the iconic Sherpa village of Namche Bazaar with Kongde Ri (6,187 m, 20,299 ft) in the back-ground. One of the most dramatic aspects of the geomorphology of the Greater Himalaya in general and the Khumbu specifically is the spectacular convexity of deeply incised river valleys. Valley profiles are steepest (nearly vertical) right above river channels, but gradually "lay-back" at higher elevations. This gives the impression that erosion is barely keeping up with tectonic uplift. Also note extreme gradients of tributary "channels" (most are avalanche chutes) above the Bhote Koshi River cut into bedrock below Namche Bazaar.



View looking south down the Khumbu Valley from a vantage point just north of Namche Bazaar showing dramatic valley profile convexity. Near-vertical valley flanks near the Dudh Koshi River channel increase the risk from earthquake- and monsoon-induced mass movements, particularly on perched benches of unconsolidated glacial or alluvial sediment.

View looking southward over the village of upper Pangboche at steep east-dipping metamorphic foliation in the Namche orthogneiss which controls valley profile convexity in this area. Valley profile convexity is most apparent in distant profiles.

Valley profile convexity dramatically lessens north of Phortse where the effects of alpine glaciation have modified the landscape. Nevertheless, extreme hazards associated with ground shaking exist, including rock falls, glacial outburst floods (GLOFS), avalanches from perched glaciers, and failure of steep glacial moraine deposits, to name a few. This photo shows the Everest massif, with Nuptse, Everest and Lhotse (left-to-right) in the distance, with the Imja Khola River in the channel.

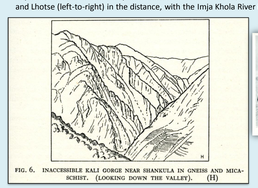
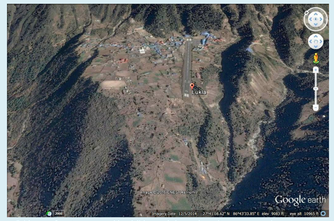


FIG. 6. INACCESSIBLE KALI GORGE NEAR SHANKULA IN GNEISS AND MICA-SCHIST. (LOOKING DOWN THE VALLEY). (H)

A. Gansser, 1936

"The convexity of the walls of such valleys is the outcome of the increasing erosive power of the rivers, this in turn being due to the steady increase in the height of the mountains." Quote from Arnold Heim and Augusto Gansser, The Throne of the Gods: An account of the first Swiss expedition to the Himalayas (1939)

Earthquake-triggered mass movements (past & recent):



Evidence of past compound landslides and slump deposits, some massive, are common along the flanks of the Dudh Koshi River north of Lukla. The bench on which Lukla is built is riddled with enormous angular boulders adjacent to the Hillary landing strip; this large landslide likely dammed the Dudh Koshi River (Götz et al., 2015).

The high Sherpa village of Pheriche is located on a glacial ground moraine surrounded by high lateral moraines. Ground shaking of water saturated glacial sediment resulted in significant damage (inset photo).

This boulder (photo above) lies along the main trekking trail that passes through Ghat; the many painted Mani stones at Ghat are debris from a massive paleo-landslide. Unconsolidated, hummocky and often water-saturated deposits like this form a poor substrate for field-stone buildings when earthquakes strike. Other villages that are constructed on unconsolidated landslide debris, perched high above adjacent rivers, include Khumjung and Namche Bazaar.

Coalesced coarse talus/scree/alluvial cones at the base of Taboche Peak (6367 m; 20,889 ft.), overlain by a massive rock avalanche deposit that has been truncated at its toe by the Lobuche Khola River (which drains directly from the Khumbu Glacier at the foot of Mount Everest). Although this deposit was not triggered by the 25 April 2015 Gorkha earthquake, ancient rock avalanche deposits of this magnitude are good analogues for earthquake hazard analysis in the high alpine valleys of the Greater Himalaya. Note the yak pastures and huts below the slide. A major GLOF hazard lies just behind the terminus of Chola Glacier at the base of Arakam Tse.

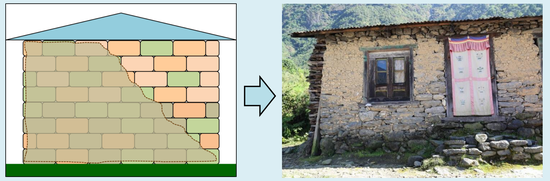
Large earthquake-induced landslide on the west flank of the Dudh Koshi River immediately north of Phakding above the Dudh Koshi River. Workers have started rebuilding the trail across the slide-path (Oct. 2015), despite obvious unstable perched boulders above. The unconsolidated and heterogeneous nature of the coarsely-stratified sediment is obvious.

Yak pasture with a fence constructed of dry-stacked "field stones" (no mortar) was toppled during the 2015 Gorkha earthquake sequence. This yak pasture complex is located on the high NE lateral moraine (Khumbu Glacier) between Pheriche and Dughla. Unsupported top-heavy construction, unstable substrate, and possible amplification of ground shaking on the moraine crest all contributed to failure.

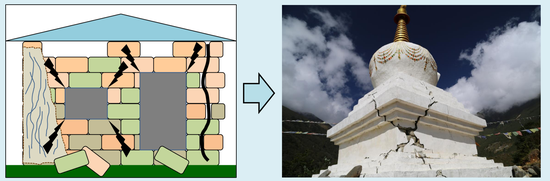
ABOVE: Lower portion of the landslide scar (see photo above) on the west flank of the Dudh Koshi River immediately north of Phakding above the Dudh Koshi River. Heterogeneity of the sediment is a mirror image of that higher up. **BELOW:** Twin landslides from the 25 April 2015 earthquake in perched unconsolidated sediment of mixed sources along the Dudh Koshi River between Ghat and Phakding.

ABOVE: Ladder crossing of crevasses in the Khumbu Icefall above Everest Base Camp. Shown in red is the break-away zone (between Pumori and Lingtren) and run-out path (air blast zone) of the massive ice/snow avalanche on 25 April 2015 that swept across Base Camp and killed over 20 people. Photo taken in April 2012 during the MSU/Nat Geo/TNF Everest Education Expedition. **BELOW:** Prayer flags on the bridge over the Dudh Koshi River below the Sherpa village of Phortse.

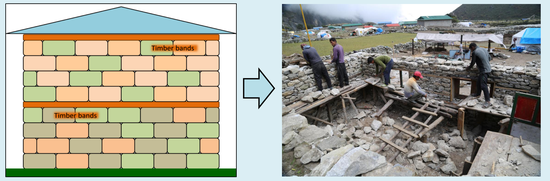
Traditional and new construction methods:



Older, traditional buildings in the Khumbu were constructed of uncut "field stone" with no mortar or external plaster, just small stones placed between larger stone blocks to fill gaps; some buildings used dried mud mortar as an external "plaster," as shown in the diagram and photo above (Lukla).



"X-cracking" of external structural walls was common damage from the Gorkha earthquake, often with cracks originating from corners of windows and door jams. Large, through-going sub-vertical cracks were also common, along with toppling of stones at the top of walls and from triangular spaces directly under roofs. The Buddhist stupa above, just west of Namche Bazaar, shows a dramatic example of x-cracking at a corner.



Traditional construction methods throughout many parts of the Himalaya have utilized hand-cut stone blocks with wood spacers, called "timber bands" or "tie beams." Timber bands tend to isolate smaller portions of a stone wall relative to seismic shaking, thus preventing the entire wall from undergoing catastrophic failure. Timber bands, carved into decorative snakes, are clearly seen in Kathmandu on Hanuman Dhoka Palace (yellow arrows in photo below) in Durbar Square. The old palace experienced far less damage from the Gorkha earthquake than did the newer addition to the palace (white building to the left).

Example of insufficient timber banding in the wall in a small structure in Phakding; the wood boards do not go through the entire wall and did not support the wall during seismic shaking, resulting in catastrophic failure.

Rebuilding the Khumbu:

Buildings constructed in the aftermath of the 2015 Gorkha earthquake show great variety in the degree to which materials are used to mitigate future seismic damage, depending on available resources. The spectrum includes:

1) hand-cut rectangular stone blocks with dried mud mortar and external mud plaster
2) Hand-cut stone with cement mortar (rare)
3) Hand-cut stone with wire-mesh wrap (**Gabion bands**), with or without mud or cement mortar
4) Hand-cut stone with wood spacers, as described above
5) **Metal sheet siding on upper levels of multi-story structures, instead of stacked rock blocks or field stone;** this is expensive but provides for a safer dwelling during seismic ground shaking

Wire-mesh gabion walls are used in conjunction with expensive steel-frame construction at the Khumbu Climbing Center in the Sherpa village of Phortse, resulting in a reasonably strong structure that withstood seismic shaking in 2015.

Spectrum of structural damage:

This is typical of structural damage in the Khumbu region. Failure occurred at the top of external rock walls (unreinforced masonry), leaving inside wood paneling exposed but relatively intact. It is likely that this rock wall will be rebuilt in the same style as before the earthquake, due to lack of resources.

Catastrophic failure of a traditional Khumbu building (stacked field stone – URM).

Catastrophic failure of a traditional Khumbu building (stacked field stone with external plaster) near Thame. The entire structure is on the verge of collapse (red circle). An elderly man lives here with a young yak, residing in a small tent on the opposite side of the building.

ABOVE: Catastrophic failure of roof and walls of a traditional Khumbu building (stacked field stone with external plaster) near Thame. **BELOW:** Thame experienced massive damage during the Gorkha earthquake and its aftershock sequence; this famous Sherpa village was constructed on water-saturated ground moraine and outwash between high lateral moraines. Many people still live in make-shift shelters of tarps, sheet metal, or whatever else can be salvaged.